OFFICE OF NAVAL RESEARCH ANNUAL GRANT REPORT

Nanometer-Scale Thermal Processing for Advanced Manufacturing (YIP'96)

FIRST ANNUAL REPORT: MAY 1, 1996 - April 30, 1997

Graduate Students:	William P. King, Daniel A. Fletcher, and Y. Sungtaek Ju
Stanford Advisor:	Prof. Kenneth E. Goodson
ONR Director:	Dr. Richard G. Brandt
ONR Grant Number:	N00014-96-0688

1. SUMMARY

We have made progress on nanoscale temperature control for advanced manufacturing using two different approaches based on scanning probe technology.

The first approach is NSOM-based and uses radiation interaction at the tip of a tapered, metal-coated optical fiber. This approach offers the advantage of very brief (<< 1 μs) heating and temperature detection. To aid with the development of this approach, we have performed extensive far-field laser-reflectance thermometry studies with high spatial and temporal resolution (0.5 μm, 10 ns). We have developed an NSOM-based facility for temperature control studies using the optical fiber. The facility directs radiation from a steady Ar ion probe laser and a pulsed Nd:YAG laser onto samples through the optical fiber. This facility has been used to demonstrate near-field laser-reflectance thermometry for the first time. We have also demonstrated the cutting of interconnect structures using radiation from the pulsed laser. Simultaneous processing and temperature detection is a major goal for the coming year. We also aim to demonstrate near-field *infrared* thermometry, which promises improved sensitivity and may be most useful as a diagnostics tool for the IC industry.

The second approach uses Joule heating at the tip of AFM cantilevers to aid with nanoscale forming and cutting processes performed using the tip. This approach offers the advantage of precise tip-surface force control. This work is being performed collaboratively with a MEMS group at Stanford (Prof. T. Kenny) and researchers at IBM Almaden (Drs. J. Mamin and D. Rugar), who have been developing related technology for data storage applications. This research effort is modeling the transient temperature field in the cantilever and has made approximate measurements of the tip temperature using electrical and laser-reflectance methods. We are in the process of developing cantilevers with faster thermal time constants. During the coming year, we aim to provide detailed data and simulations for material thermally-assisted material removal processes using this technology.

2. PROGRESS ON THERMOMETRY AND PROCESSING USING OPTICAL METHODS

We have developed high-resolution (0.5 μm, 10 ns) far-field scanning thermometry technology, which provides foundations for our progress on near-field heating and temperature control at surfaces. The far-field measurements are based on a facility that integrates scanning laser optics with high-resolution electrical-probing capability. Two rotating mirrors scan highly-focussed laser light over the surface of integrated circuits and MEMS. Radiation is collected using a photodiode with 500 MHz bandwidth, allowing rapid modulations in the reflectivity of the surface to be monitored. Calibration of the temperature dependence of the reflectivity yields transient temperature field data. This technique, which we call scanning laser-reflectance thermometry, is used for thermal diagnostics of MEMS and IC structures with unprecedented temporal resolution. This technique has recently been used to map temperature fields in semiconductor devices [4]. Figure 1 temperature-field data for aluminum-alloy interconnects pulse heated using electrical currents of duration 250 ns [11,17,18]. The transient temperature distributions and optical property data obtained from these measurements are being compared with those obtained using an optical fiber, described below, whose main application is for temperature control and process monitoring during surface modification.

Near-field thermometry and processing are being studied using the facility shown in Fig. 2, which we have developed during the first year of this award with support from ONR and the Stanford University School of Engineering. This facility allows heating of the sample by means of nanosecond pulsed radiation with simultaneous monitoring of the radiation reflected within the fiber and transmitted or reflected by the sample within the optical enclosure. The reflected radiation can be used for thermometry [6, 23], using principles similar to those behind the far-field thermometry described above. A Nd:YAG pulsed heating laser and a steady Ar ion probe laser are coupled into the single-mode fiber. The pulse heating energy is controlled using a liquid-crystal attenuator. The optical enclosure is a modified commercial NSOM, which scans the tapered, metal-coated fiber tip above the surface of the sample using the shear-force feedback mechanism. A photomultiplier tube (PMT) within the enclosure captures radiation reflected by or transmitted through the surface.

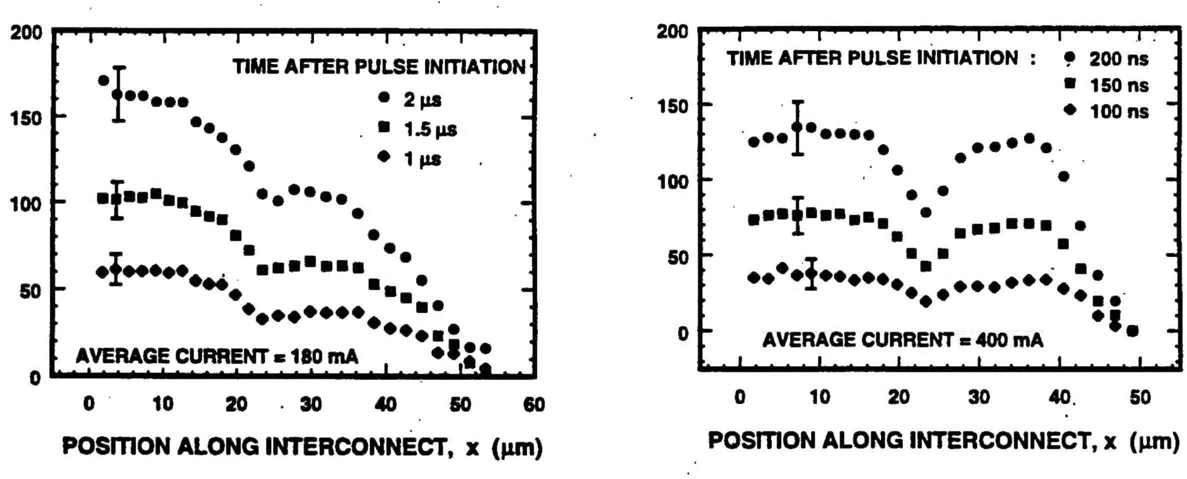

Fig. 1 Transient temperature distributions along interconnect structures subjected to currents of varying duration [18]. The temperature distribution is symmetric about the coordinate $x = 0$. The interconnects have a corner at $x = 25$ μm and reach a contact pad, where there is no heat generation, at $x = 50$ μm. The temperature rise at the corners is reduced because the ratio of the rate of the heat generation rate to the metal volume is locally reduced.

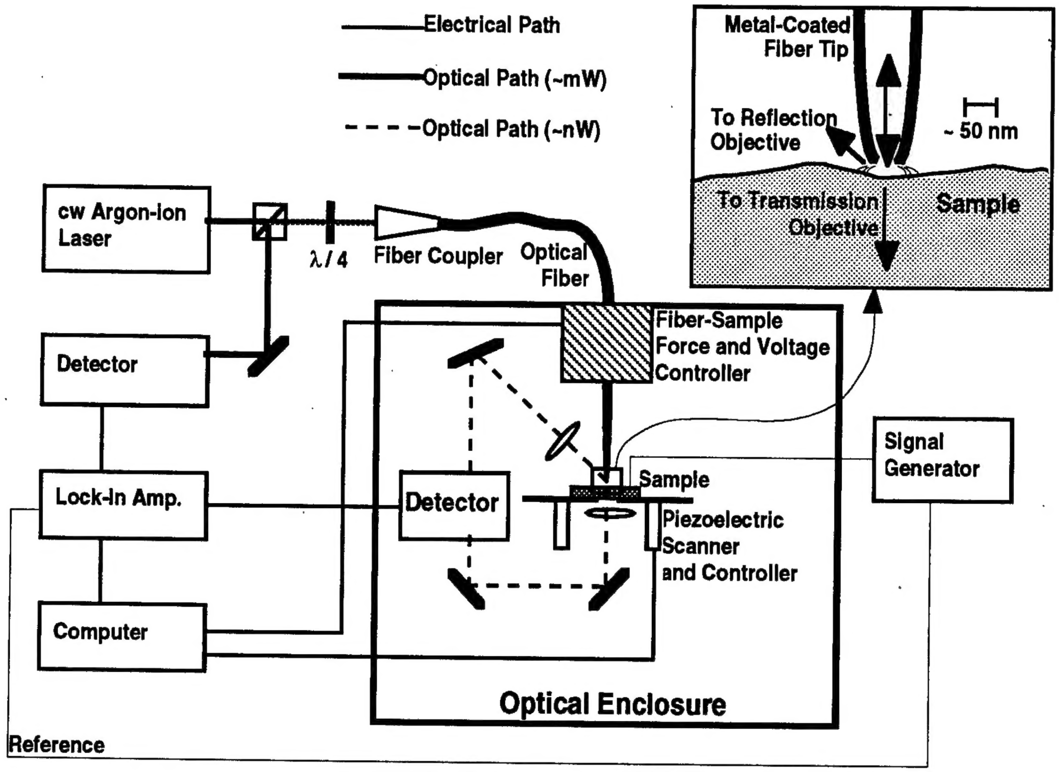

Fig. 2 Facility for investigating laser processing and thermometry using near-field radiation interaction at the tip of an optical fiber.

We have proposed near-field optical thermometry using a four distinct optical paths, which are summarized in Table 1 [6, 23]. We have made the most experimental progress using path 1 and together with heating of electronic microstructures in the frequency domain. The fiber is suspended a few nanometers above the surface of the sample and the transient fluctuations in the radiation intensity are monitored. A lock-in amplifier measures the amplitude and phase of the collected radiation intensity at the heating frequency f, which is twice the frequency of the bias current. The calibration of the temperature amplitude corresponding to a given radiation amplitude is performed using a two-step procedure. First, the transient NFOT data are taken above a calibration bridge whose temperature can be assumed uniform and whose electrical resistance can be measured simultaneously. Second, the temperature dependence of the electrical resistance of the bridge is calibrated independently using a probe station and a thermal chuck. The calibration can only be considered appropriate for surfaces that closely resemble the calibration surface in roughness, purity, and stoichiometry. By studying the amplitude and phase of the induced radiation intensity oscillations, we have been able to draw conclusions about the relative importance of the temperature dependence of the optical properties of the sample and the tip-surface separation [6, 23].

Table 1 Summary of near-field optical thermometry techniques that can be pursued using the facility in Fig. 2 [6, 23].

Near-Field Thermometry Technique	**Radiation Source**	**Collection Path**	**Comments**
1. Laser reflectance, far-field collection	probe laser through optical fiber	far-field objective above sample	Data provided in this manuscript in Figs. 2 and 3. Resolution impaired somewhat by optical path around fiber tip.
2. Laser reflectance, fiber collection	probe laser through optical fiber	optical fiber, $\lambda/4$ plate, beam splitter	Radiation reflected from surface may prove impossible to extract from radiation reflected within fiber.
3. Laser transmittance	probe laser through optical fiber	far-field objective beneath sample	Appropriate only for samples that are not opaque.
4. Infrared emission	sample surface infrared emission	infrared-transmitting optical fiber	Possibility for large sensitivity. Dramatic improvement over far-field resolution, which is comparable to 5 μm at room temperature.

We have made progress on the modification of surfaces using near-field irradiation [23]. The important fundamental discovery in this area has been analytical in nature and relates to a new parameter we have defined, η, which is the ratio of the peak temperature rise in the surface to that in the probe. Effective thermal processing must maximize η to prevent damage to the probe. Thermal analysis has predicted that if the heating laser has a pulse duration longer than a few nanoseconds, heat transfer to the sample surface will be dominated by thermal conduction from the heated tip through an adsorbed moisture layer. In the absence of an adsorbed layer, the temperature rise in the sample will be negligible. For this case, it is impossible to achieve a higher temperature rise in the sample than in the tip of the fiber. This is also analogous to the generation of heat using the tip of an AFM cantilever, which is described in the following section. If the pulse duration is briefer than a few nanoseconds, it is possible that the thermal capacitance of the fiber can strongly reduce its temperature rise compared to the temperature rise of the region absorbing radiation at the sample surface. This near-field illumination can dramatically increase the parameter η by using direct irradiation, rather than conduction, to transfer energy to the surface. Experimentally, we have investigated the local heating and cutting interconnects of width 1 μm using the Nd:YAG laser. The interconnects were modified without noticable damage to the fiber tip. We have not yet established the primary mode of energy transfer during this initial experimental processing work.

3. THERMAL NANOMACHINING USING THE AFM

We have been using ONR support to investigate thermal machining at nanoscales using an AFM-based approach. There have been limited studies on using the AFM to modify surfaces for lithography and high-density data storage, in some cases using the AFM cantilever tip to locally apply heat and mechanical force. One approach for heat deposition is the use of a bias current along the cantilever, an approach which has made possible highly-localized indentation of polymers [13]. Previous research has not, however, attempted to precisely control the surface temperature or to model the complex thermal and mechanical tip-surface interactions. We are performing this work in collaboration with the Stanford University research group of Prof. T. Kenny and with Drs. J. Mamin and D. Rugar at IBM Almaden.

This research investigates the physics by which heat and force interact to modify surfaces at nanometer lengthscales. Initial experiments have used far-field laser-reflectance thermometry to study transient heat generation and diffusion in the cantilever in the absence of tip-surface contact. Extraction of the transient temperature data has been complicated by the thermomechanical deflection of the cantilever, which induces decaying periodic laser intensity fluctuations with temporal period near 80 μs. We are in the process of modeling the indentation of the polymer surface as a function of the duration and magnitude of voltage pulses applied along the cantilever and of the tip-surface force. We are also developing specialized cantilevers that minimize the heating time constant and maximize the fraction of heat deposited in the cantilever that enters the surface of the sample.

The goal of this research is to provide foundations for practical thermal nanomachining tools based on the AFM that perform novel forming, soldering, and cutting processes at nanoscales. AFM thermal machining offers capability that is distinct from conventional lithography because it promises three-dimensional manipulation with the assistance of localized heating.

4. KEY GOALS AND MILESTONES FOR THE COMING YEAR

Thermometry and Thermal Processing using NSOM Technology

- Near-field infrared imaging
- Demonstration of surface modification using direct near-field laser irradiation rather than tip-surface conduction
- Simultaneous near-field heating and thermometry of surfaces

Thermal Nanomachining using AFM Technology

- Development of robust cantilevers with thermal time constants well below 1 μs
- Simulation and experimental demonstration of thermally-assisted cutting

5. PUBLICATIONS AND CONFERENCE APPEARANCES

All publications listed here were either submitted, accepted, or published during the first year of the ONR YIP'96 award. All conference appearances occurred or were invited during the first year, as well. **Those publications in bold were made possible by ONR support.**

Major Book Chapter

1. **Goodson, K.E., Ju, Y. S., and Asheghi, M., "Thermal Phenomena in Semiconductor Devices and Interconnects," to appear as a chapter in *Microscale Energy Transport*, Begell, New York.**

Manuscripts in Archival Journals

2. Goodson, K.E., 1996, "Thermal Conduction in Nonhomogeneous CVD Diamond Layers in Electronic Microstructures," *ASME Journal of Heat Transfer*, Vol. 118, pp. 279-286.

3. Goodson, K.E., Kurabayashi, K., and Pease, R.F.W., "Improved Heat Sinking for Laser-Diode Arrays using Microchannels in CVD Diamond," *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part B: Advanced Packaging*, Vol. 20, pp. 104-109.

4. **Ju, Y.S., Käding, O.W., Leung, Y.K., Wong, S.S., and Goodson, K. E., 1997, "Short-Timescale Thermal Mapping of Semiconductor Devices," *IEEE Electron Device Letters*, Vol. 18, pp. 169-171.**

5. Touzelbaev, M.N., and Goodson K.E., "Impact of Nucleation Density on Thermal Resistance Near Diamond-Substrate Boundaries," *AIAA Journal of Thermophysics and Heat Transfer*, in press.

6. **Goodson, K.E., and Asheghi, M., "Near-Field Optical Thermometry," *Microscale Thermophysical Engineering*, Vol. 1, in press.**

7. Asheghi, M., Touzelbaev, M.N., Goodson, K.E., Leung, Y.K., and Wong, S.S., "Temperature-Dependent Thermal Conductivity of Single-Crystal Silicon Layers in SOI Substrates," submitted to *ASME Journal of Heat Transfer*.

8. Asheghi, M. , Käding, O. W., Goodson, K. E., Leung, Y. K., Wong, S. S., Suzuki, Y., 1996, "Transient Thermometry of SOI Power Transistors using Microfabricated Thermistors," submitted to *IEEE Transactions on Components, Hybrids, and Manufacturing Technology Part A*.

9. Kurabayashi, K., and Goodson, K. E., "Precision Measurement and Mapping of Die-Attach Thermal Resistance," submitted to *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part B: Advanced Packaging*.

10. **Ju, Y. S., and Goodson, K. E., 1997, "Short-Timescale Thermal Mapping of Interconnects," submitted to *IEEE Electron Device Letters*.**

11. **Ju, Y. S., and Goodson, K. E., 1997, "Short-Timescale Thermal Mapping of Microdevices using a Scanning Thermoreflectance Technique," submitted to *ASME J. Heat Transfer.***

12. Ju, Y. S., and Goodson, K. E., "Size Effect on the Thermal Conductivity of SOI Device Layers," submitted to the *Japanese Journal of Applied Physics.*

13. **Chui, B.W., Stowe, T.D., Ju, Y.S., Goodson, K.E., Kenny, T.W., Mamin, H.J., Terris, B.D., Ried, R.P., and Rugar, D., 1997, "Low-Stiffness Silicon Cantilevers with Integrated Heaters and Piezoresistive Sensors for High-Density AFM Thermomechanical Data Storage," submitted to the *ASME/IEEE Journal of MicroElectroMechnical Systems.***

Manuscripts in Refereed Conference Proceedings

14. Goodson, K.E., Ju., Y.S., Asheghi, M., Käding, O.W., Touzelbaev, M.N., Leung, Y.K., and Wong, S.S., 1996, "Microscale Thermal Characterization of High-Power Silicon-on-Insulator Transistors," *Proceedings of the 31st ASME National Heat Transfer Conference, Houston, Texas, August 3-6,* Vol. 5, R. L. Mahajan et al., eds., pp. 1-9.

15. Touzelbaev, M.N., and Goodson K.E., 1996, "Impact of Nucleation Density on Thermal Resistance Near Diamond-Substrate Boundaries," *Proceedings of the ASME National Heat Transfer Conference, Houston, Texas, August 3-6,* Vol. 5, R. L. Mahajan et al., eds., pp. 193-200.

16. Asheghi, M., Touzelbaev, M.N., Goodson, K.E., Leung, Y.K., and Wong, S.S., "Temperature-Dependent Thermal Conductivity of Single-Crystal Silicon Layers in SOI Substrates," presented at the *International Mechanical Engineering Congress and Exposition, Atlanta, GA, November 17-22,* DSC-Vol. 59, in *Micro-Electro-Mechanical Systems (MEMS),* C. T. Avedisian et al., eds., pp. 83-91.

17. **Ju, Y.S., and Goodson, K.E., "Short-Timescale Thermometry and Reliability Studies of Metal Interconnects in VLSI Circuits," presented at the *International Mechanical Engineering Congress and Exposition, Atlanta, GA, November 17-22,* DSC-Vol. 59, in *Micro-Electro-Mechanical Systems (MEMS)*, C. T. Avedisian et al., eds., pp. 31-36.**

18. **Ju, Y.S., and Goodson, K.E., 1997, "Short-Timescale Thermal Mapping of Interconnects," Proceedings of the *35th IEEE International Reliability Physics Symposium*, Denver, Colorado, April 8-10, IEEE Catalog No. 97CH35983, pp. 320-324.**

19. Kurabayashi, K., and Goodson, K. E., 1997, "Precision Measurement and Mapping of Die-Attach Thermal Resistance," to be presented at *INTERpack '97,* June 15-19, Mauna Laui, Hawaii.

20. Schuder, R. G., and Goodson, K. E., "Integrated Circuits and MicroElectroMechanical Systems in the Heat Transfer Teaching Laboratory," to be presented at the *1997 National Heat Transfer Conference*, Baltimore, Maryland, August 7-10.

Invited Speeches

21. Invited Speaker, "Impact of Diamond and Related Materials on the Thermal Engineering of Microdevices," *Diamond '97: 4th International Conference on the Applications of Diamond Films and Related Materials / 8th European Conference on Diamond, Diamond-Like, and Related Materials*, Edinburgh, Scotland, August 3-8, 1997.

22. Invited Speaker, "Impact of Microscale Thermal Phenomena on Semiconductor Thermal Processing," *5th International Conference on Advanced Thermal Processing of Semiconductors*, September 3-5, 1997.

23. **Invited speaker, NSF-sponsored *U.S.-Japan Seminar on Molecular and Microscale Transport Phenomena*, "Towards Temperature Control at Nanoscales using a Tapered Optical Fiber," Santa Barbara, California, August 8-10, 1996.**